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NEUTRON DETECTION STUDIES IN BARE PHOTO TUBES USING COLD NEUTRONS AT NIST

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Summary:

To explain the high single-photo-electron rates in Philips XP4572B photomultiplier tubes used in a G0 experiment Cerenkov detector, a study was done with collimated cold neutrons interacting in the glass (window, sides) of such tubes. Each neutron absorbed in the boron in the borosilicate glass of the tube's front window yields up to about 4 photo electrons, which are spread in time such that on average 3.5 time-separated events per neutron are recorded. Quartz and lime-glass window tubes show much smaller numbers of detected photo electrons. The glass envelops of all tubes also show some signals from neutron absorption. For the 5" XP4572B the integrated rate of the glass envelop is estimated to be 5% to 20% of the rate from the front window. Any gammas from neutrons interacting in iron shielding or boron-containing shielding contribute negligibly to count rates in the photo tubes (< 10%).

I. Introduction:

The G0-Experiment at Jefferson Laboratory uses Cerenkov aerogel detectors with 5" photo multiplier tubes to separate electrons from pions. When switching from a liquid hydrogen to a liquid deuterium target, the count rates recorded by the photo tubes increased much more than expected. It was verified, by isolating a photo tube from the Cerenkov detector volume, that more than 80% of the count rate originates in the photo tubes proper.

The observation that these 5" Photonis (XP4572/B) tubes have borosilicate windows, in connection with the large number of neutrons emitted from deuterium when interacting with the electron beam, raised the suspicion that neutron absorption in the boron of the tube's glass window and envelop might be the origin of the high count rates. Neutron absorption on ^{10}B, with a very

high cross section for low energy neutrons, results in decay products of an alpha plus a ^{7}Li, which deposit several MeV of energy in the glass. Specifically,

^{10}B+n -> ^{7}Li + α + T[2.79MeV] (6% probability),

-> ^{7}Li + α + T[2.31MeV] + gamma [0.48MeV] (94% probability)

The decay products produce scintillation light in the glass, releasing photo electrons in the active photo cathode on the window of the tube. MC studies indicated that the expected neutron absorption rates are still smaller than the count rates observed.

So the questions for which we wanted answers are:

(a) Does neutron absorption in the photo-tube glass produce detectable scintillation light, i.e., do we observe photo-electrons in the tube?

(b) If we detect photo electrons from neutron absorption, how many do we detect and are they prompt or are they spread out in time into several individual signals (phosphorescence in the glass)?

(c) If we replace the active window of the photo tube by a quartz window, how much light do we see from the remaining glass envelop of the tube?

(d) Do neutron-created gammas from iron shielding already present or prospective boron-containing shielding create large photo tube rates?

(e) If we replace the active window of the photo tube by a quartz window, will this quartz window create signals from sources other than neutron absorption in boron?

Questions (a) to (d) can be ideally investigated with a tightly collimated cold neutron beam available at NIST; all neutrons from such a beam are absorbed in the borosilicate glass. This allows one to study quantitatively the photo-electron detection from neutron absorption for different parts of photo tubes. The results can easily be extrapolated to any neutron energy given the well-known energy-dependent neutron absorption cross sections on ^{10}B since the decay product energy depends only weakly on neutron energy (for our below-1-MeV region).

Question (e) can only be partially answered, i.e., only for the low energy part of the neutron spectrum in the G0 experiment. Higher energy neutrons and other particles may contribute to any count rates due to processes other than neutron-on-boron absorption.

II. Experimental setup and data acquisition

1. Beam:

- We used a mono-energetic cold neutron beam (3.3 meV, 4.95 Å);
- Beam diameter was collimated to between about 9 and 16 mm (estimate) depending on distance from the 3.2 mm thick Boraflex collimator (Boraflex: B^4C in silicon elastomer, probably 31.5% B by weight);

- The neutron rate was measured with a fission chamber which has an efficiency of 0.375e-3 (+- 5%);
- Fission chamber rate was 62.8 Hz, thus a nominal neutron rate of 167 kHz.

2. Detectors (photo tubes):

- one 5" borosilicate window tube Philips XP4572/B, (G0 5" Cerenkov detector);
- one 2" quartz window tube Hamamatsu R375 (G0 luminosity monitor);
- one 2" lime glass window tube Philips XP2262B (G0 NA FPD/CED detector).

- Detectors were mounted in enclosures designed to minimize neutron absorption/scattering (hydrogen is very bad at these low energies).
- Loss of neutrons from enclosure materials was measured and the results are corrected for those losses; for the results presented here the corrections were less than 15% (except for XP2262B tube which had a silicone cookie left on the front face).
- Detectors were shielded by mu-metal, the 5" tube only up to the face of the tube.
- Detectors were mounted
  (a) tube face staring at oncoming neutron beam; different positions were done moving sideways, to scan across the entrance window face;
  (b) tube mounted so that the beam goes parallel to the entrance window; a series of positions were measured to investigate the position dependence of light from the envelope part of the tubes;
- for the gamma rate estimates, the 5" tube was mounted facing the neutron beam and different absorbers were placed in the beam.

3. Electronics and data acquisition:

- the HV was adjusted to yield about 10 mV per single photo electron (SPE);
- the signal was amplified by a factor of ten: SPE = 100 mV;
- different discriminator thresholds used: 40 mV, 150 mV, 200 mV;
- discriminator output width: normally 20 nsec; for decay time measurements 5ns (reference counts) and 50 ns to about 200 micro seconds ("dead timed" counts for decay time constant measurement) [not yet analyzed];
- signals go into visual scalers; several 1-sec intervals were counted and recorded by hand (photo-tubes) or 100-sec intervals (fission chamber).

III. Results

1. Direct Observations During Data Taking

More than 80 % of all triggers are SINGLE PHOTO ELECTRON events.

- Counts from a threshold of 150 mV (1.5 PE) still seem to be dominated by the high-signal tail

of the SPE distribution.

- When the oscilloscope is triggered (40 mV or 200 mV) there are plenty of other signals visible to the right (later), but very few, if any on the left; this is best visible for time scales of 1 to 10 micro-sec (Fig. 1).

Figure 1. Oscilloscope photograph showing numerous signals following the trigger, and very few prior to the trigger. Settings are 500mV and 1.0 micro second per division.

- For the 5" borosilicate tube we get (at 40 mV discriminator) a count rate of about 600 kHz; thus we get about 3.5 individual SPE events per neutron in the beam. Most signals come "long" after the first signal is detected.
- All neutrons are stopped in the borosilicate glass.

2. Data Taken and Analysis:

The raw count rates were corrected for the dark count rate (rate with no beam) and normalized by the fission-chamber deduced neutron-beam rate. In addition, the data were corrected for losses in the walls of the light tight containers surrounding the tubes. These losses were determined independently by placing the material in question between two

fission chambers and recording the loss in rate due to the material. This procedure may somewhat over correct the data, since the photo tubes may see scattered neutrons which are not seen by the second fission chamber.

The corrected measured data are given in the tables located at the end of this document; tables A1 and A2 are for the borosilicate window 5" tube, tables B1 and B2 for 2" quartz window tube, and tables C1 and C2 for the lime-glass window tube. The raw rates, together with the no-beam rate allows an estimate of the statistical uncertainties for the one second measurements, which are much smaller than systematic uncertainties and are of the order of 10%. For reference, the data are also expressed as signals per neutron in the tables.

Table A1 also shows results for rates taken with a threshold equivalent to 1.5 simultaneous photo-electrons (150 mV). Note that this threshold is not high enough to eliminate all SPE events. It is obvious that the rates for events which may contain two or more photons are much lower than the SPE event rates.

The data for tables A1, B1, and C1 are also plotted in figure 2 as full points connected by solid lines. For easier comparison of the shapes of the distributions, the 2"-tube data are also plotted multiplied by a factor of 20 as open points connected by dot-dashed lines.

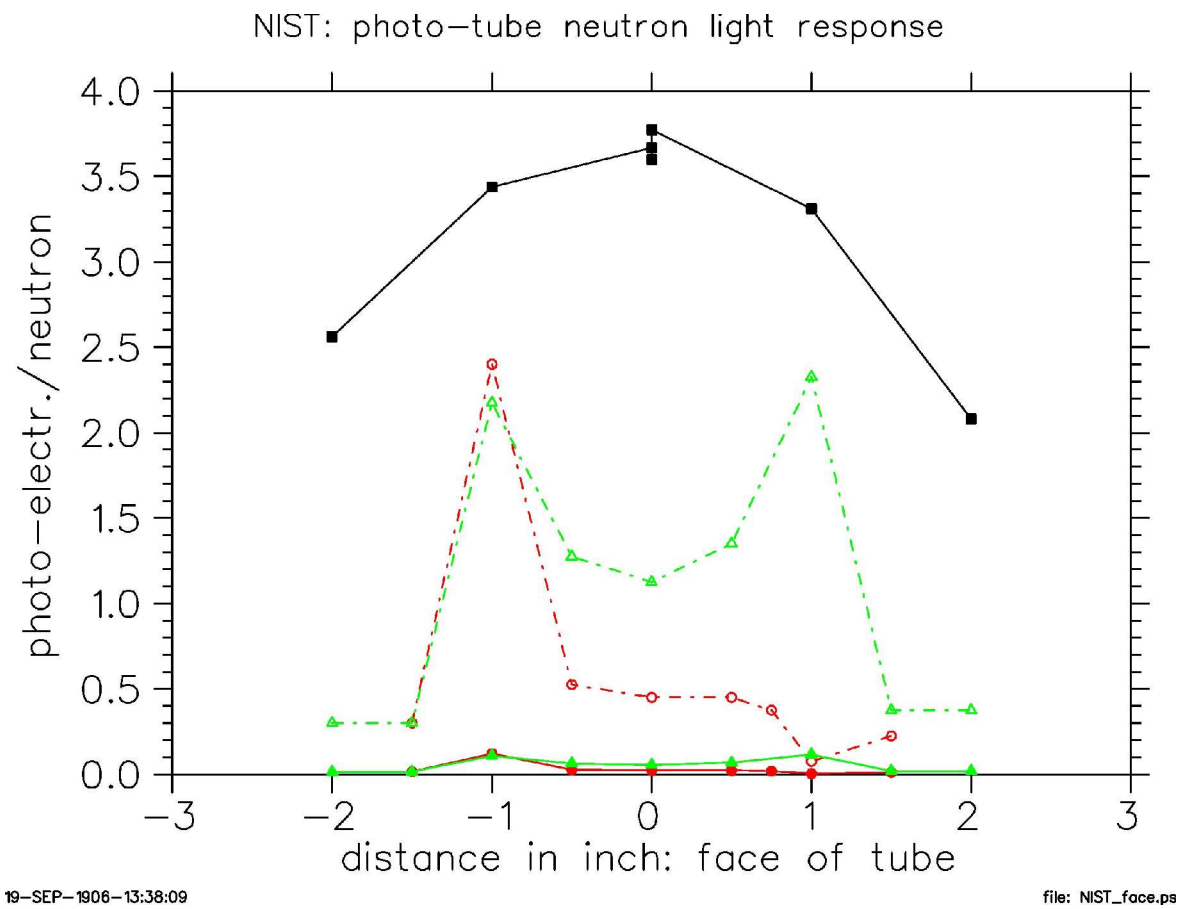

Figure 2. Count rate per neutron as a function of distance from the center of the photo-sensitive window across the face of the tube for the borosilicate-window 5" tube (black solid squares), the 2" quartz-window tube (red filled circles), and the 2" lime-glass-window tube (green filled triangles). The quartz and lime-glass window tube data are scaled up by a factor of 20 for the open symbols, connected by dot-dashed lines. Note that the lime-glass tube results are affected by a silicone "cookie" left in front of the window (see note for table (C)).

Figure 3 shows the data of tables A2, B2, and C2 in a similar way, except that the enhancement factor for the 2" tubes is only a factor of five.

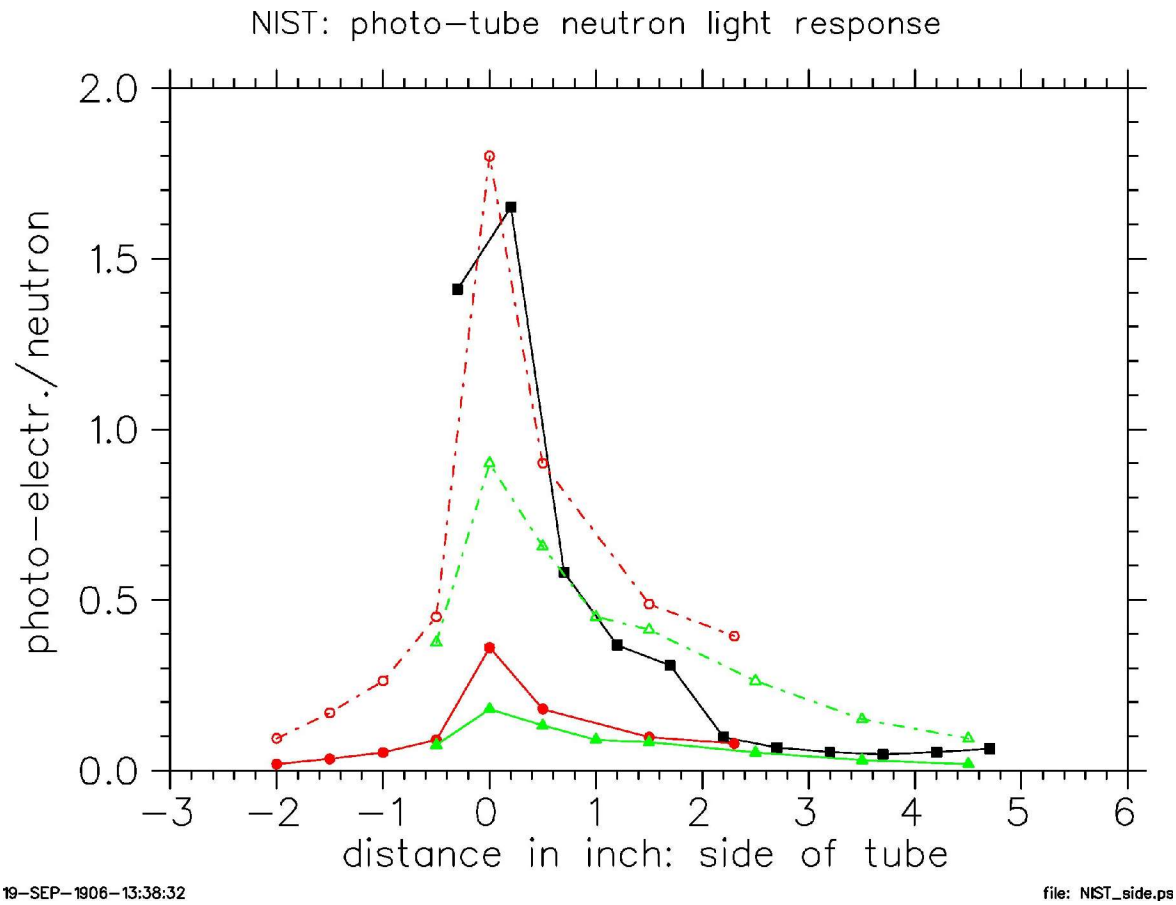

Illustration 2Figure 3. Count rate per neutron as a function of distance from the window of the tube along the side of the tube. For negative distance values the neutron beam does not directly intersect the photo-tubes; events seen are presumably due to neutron scattering in the plastic light-tight container. Symbols are the same as in figure 2, except that here the open symbols are scaled up only by a factor of 5. The data have been shifted horizontally to align the maxima at zero.

3. Results from Analysis of Data Taken:

(a) 5" borosilicate window tube:

- The 5" borosilicate tube face (Fig. 2) yields on average about 3.7 SPEs per neutron in the center of the window, decreasing to less than 2.5 SPEs at 2 inchs from the center. A rough estimate for a weighted average over the volume of the window yields about 2.5 signals per neutron.
- Scanning the side of the tube (Fig. 3) shows rates of about 1.5 signals/neutron at the window, consistent with figure. 2. The count rates then decrease from 0.6 signals/neutron near 1" from

the face to below 0.1 signals/neutron at 3" from the face. Integrating the rates weighted by the surface or volume of the glass of the tube can yield rate estimates for tubes located in a diffuse neutron environment, like the G0 experiment. A rough estimate for the contribution of signals from the tube envelope is ~ 20 % if scaled by the area (thermal or colder neutrons) or ~ 5% if scaled by the volume of the glass (eV and higher energy neutrons). Thus, eliminating the borosilicate glass window can reduce the G0-experiment neutron-produced rate by about 80 to 95%.

(b) 2" diameter quartz and lime-glass window tubes

- The centers of the entrance windows (containing no boron) of both 2" tubes (Fig. 2) show rates more than 50 times smaller than the 5" borosilicate window.
- The lime-glass window tube (green in Fig. 2) shows nicely that the envelope of the tube may contain boron, as suggested by the peaks in rates at the -1" and +1" settings. The quartz window tube (red in Fig. 2) only shows this behavior at -1", possibly due to some unexplored geometrical effect.
- Following the side of the tube (Fig. 3) we find a similar position dependence for both 2" tubes as for the 5" tube, although the 2" tubes only have about 20% of the rate. Given that the beam-spot area on the glass is independent of tube diameter and that all tube envelopes probably contain boron (see below), this decreased rate from the 2" envelop may be due to less efficient light collection from the 2" tubes' envelopes towards the photo-sensitive surface on the window as compared to the 5" tubes.
- The signal rate from the 2" tubes' envelope (~0.2) is larger than from the face window (~0.05) consistent with borosilicate glass also in both of the 2" tube's envelopes.
- The non-vanishing count rates when the beam strikes the center of the non-boron containing window of the 2" tubes is probably mainly due to neutrons scattered in the light-tight container and the window glass and then being absorbed in the boron of the envelop glass. Thus these data provide an upper limit of the rates from quartz and lime-glass windows. Taking the data at face value would indicate that the quartz glass is even better in avoiding neutron absorption than the lime-glass although geometrical effects (window thickness, envelop coverings etc.) in the tube may be the actual cause for the differences observed.

(c) Signals by gammas from neutrons absorbed in boron and iron.

Tables D1 and D2 show results for neutron absorption in combinations of iron and boron, respectively, with a lead gamma absorber. We find that if the 1/8" thick lead sheet is placed downstream (instead of upstream) of the iron or boron the rate in the tube decreases, indicating that gammas created in the iron or boron are absorbed in the lead. For boron the observed gamma rate is about 2% of the observed neutron rate in the borosilicate window of the 5" tube. While for

iron the relative rate appears to be higher it seems to be well below 10% (the limited thickness of the lead and the unknown gamma spectrum from iron allows only rather weak statements).

Thus, the (magnetic) iron shielding in the G0 setup is not the cause of the high rates. Any boron containing shielding does not produce large amounts of signals from gammas.

(d) The decay time of scintillation light after neutron absorption.

The fact that more signals are recorded than neutrons absorbed in the photo tube indicates that the scintillation light is spread over a time scale large compared to the 20 ns signal resolving time of our experiment. Indeed, on the oscilloscope it is evident that, given a signal trigger, there are more signals after the trigger than before (Fig. 1). Data were taken, with varying resolving time (dead time) to extract a time constant for the decay of the scintillation deexcitation time. The analysis is a bit more involved than expected, partially due to the relatively high count rates. Thus an attempt was abandoned since such details are not important for the G0 experiment. The raw data indicate several scintillation deexcitation time constant of 5 to 200 micro seconds.

But the G0-relevant point is clear: the photons created by one neutron do NOT come all at the same time and do not make one big signal, but rather arrive as several SPE signals.

IV. Conclusions and Application to G0 Experiment

1. Low-energy neutrons are efficiently absorbed in borosilicate glass, as expected. If absorbed in the window area, near the photo-active surface, up to an average of ~3.7 photo-electrons per absorbed neutron are detected. These photo-electrons are not released in a single few-nano-seconds wide burst, but rather are spread out over several micro-seconds, and correspondingly yielding on average 3 to 4 individual single-photo-electron signals per neutron. There are multi-photo- electron signals, but their number is comparatively small. The cold neutron beam used at NIST is absorbed near the glass surface; higher energy neutrons are absorbed anywhere in the glass, closer to the photo-cathode, and may produce slightly higher numbers of photo electrons.

2. Quartz and lime-glass tube windows suppress signals from low energy neutrons by at least a factor of 50, while the boron-containing glass envelopes of the tubes still contribute up to 0.5 signals/neutron for the 5" tubes and about 0.2 for the 2" tubes. Most likely, assuming a neutron spectrum with a wide energy spread, the count rates in the 5" tubes can be reduced by up to 95% when replacing the borosilicate window by a quartz window.

3. While the cold neutrons used in this experiment (as well as thermal neutrons) can easily be stopped in boron containing shielding (e.g. 1/8" thick FlexBoron/Boraflex blankets), one cannot as easily shield against neutrons above about 1 eV kinetic energy. Tests in the G0-beam environment showed that, for the liquid hydrogen target, a rate reduction of only less than 50% can be obtained with any geometrically possible Boraflex shielding.

4. Based in the results in this report, together with test results obtained with higher energy neutrons in Grenoble and tests in Hall C during 362 MeV G0 running, it was decided to replace all 5" Cerenkov tubes with new photo tubes with quartz windows.

5. There is no evidence that (cold) neutrons produce photo-electrons other than from capture on Boron in any amount relevant to the overall rates in the tubes studied.

6. If shielding containing boron should be used, then the secondary gammas from neutron absorption do not contribute significantly to background rates. Also, neutrons interacting in iron and lead shielding, already in place, do not produce a significant number of detected gammas as compared to the borosilicate glass originating signals.

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TABLES of rates taken with three photo multiplier tubes interacting with a collimated cold neutron beam at NIST.

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GENERAL NOTES:

- All values in tables are corrected for no-beam counts and neutron absorption in the tube's container/shielding.
- Center position is estimated with +- 1/4"; relative offsets are within about 1/10".
- Photon/neutron rates depend on the neutron flux calibration of a fission chamber with 3.75e-4 +- 5% efficiency.
- No beam: dark count rate without beam, already subtracted from with-beam rate.

(A) Photonis XP4572/B tube; 5"; borosilicate glass window

HV: ..... 1750 V
Gain: ..... SPE at about 100 mV
threshold: ..... normal at 40 mV; high at 150 mV
count rate without beam: 5 kHz
typical rate with beam: 600 kHz
time for counting: usually 1.0 sec; repeated 4 to 10 times

Table A1: scan beam across face of tube

thresh.:	40mV	150mV	40mV	150mV
	rate (kHz)		signals/neutron	
2" left	429	78	2.53	0.47
1" left	577	96	3.44	0.57
center	615	82	3.67	0.49
center again	604	73	3.60	0.43
center later	632	?	3.77	?
1" right	555	66	3.31	0.39
2" right	349	32	2.08	0.19
no beam	5.0	1.3		

Table A2: scan beam along side of tube

thresh.:	40mV rate(kHz)	40mV signals/neutron
0.0"	236	1.41
0.5"	276	1.65
1.0"	97.7	0.58
1.5"	61.7	0.37
2.0"	51.6	0.31
2.5"	16.4	0.098
3.0"	11.2	0.068
3.5"	9.1	0.056
4.0"	8.0	0.049
4.5"	9.1	0.056
5.0"	10.6	0.064
no beam	5.0	

(B) Hamamatsu 2" tube (R375); quartz window

HV: ..... 1550 V
Gain: ..... SPE at about 99 mV
threshold: ..... normal at 40 mV; high at 200 mV
count rate without beam: 25.8 kHz (40 mV); 0.3 kHz (200 mV threshold)
typical rate with beam: 29.8 kHz
time of measurement: usually 1.0 sec; repeated 4 to 10 times

Table B1: scan beam across face of quartz tube

thresh.:	40mV rate(kHz)	40mV signals/neutron
-1.5"	2.3	0.01
-1.0"	19.8	0.12
-0.5"	4.5	0.03
0.0"	3.8	0.02
0.5"	3.7	0.02
0.75"	2.9	0.02
1.0"	0.8	0.00
1.5"	1.8	0.01
no beam	26.3	

Table B2: scan beam across side of quartz tube

thresh.:	40mV rate(kHz)	40mV signals/neutron
-1.5"	3.4	0.02
-1.0"	5.4	0.03
-0.5"	8.5	0.05
0.0	15.0	0.09
0.5"	60.0	0.36
1.0"	30.3	0.18
2.0"	16.5	0.10
2.8"	13.0	0.08
no beam	26.3	

(C) Phillips 2" tube (XP2262B); lime-glass window

HV: ..... 2100 V
Gain: ..... SPE at about 106 mV
threshold: ..... normal at 40 mV
count rate without beam: 0.8 kHz (40 mV); 0.1 kHz (200 mV threshold)
typical rate with beam: 10 kHz
time of measurement: usually 1.0 sec; repeated 4 to 10 times

NOTE: a 3 mm thick transparent Silicone "cookie" was inadvertently left on the face of this tube. This cookie does attenuate (up to ~50%) and scatter the neutron beam, also into the envelope of the tube, for the table C1 setup. No corrections have been applied for this.

Table C1: scan across face of lime-glass faced tube

thresh.:	40mV rate (kHz)	40mV signals/neutron
-2.0"	2.5	0.01
-1.5"	2.3	0.01
-1.0"	18.2	0.11
-0.5"	10.9	0.06
0.0"	9.4	0.06
0.5"	11.1	0.07
1.0"	19.5	0.12

1.5"	3.0	0.02
2.0"	2.8	0.02
no beam	0.6	

Table C2: scan along side of lime-glass faced tube

thresh.:	40mV rate (kHz)	40mV signals/neutron
9.0"	12.4	0.08
8.5"	30.4	0.18
8.0"	22.0	0.13
7.5"	15.3	0.09
7.0"	13.8	0.08
6.0"	8.7	0.05
5.0"	4.4	0.03
4.0"	2.8	0.02
no beam	0.6	

(D) Gammas created by neutrons interacting with iron and boron

Method: place 1/8" thick lead sheet in front or behind material of interest for neutron interactions. Measure signal rate in 5" borosilicate window tube and compare to no-material rate to obtain attenuation factors (rate-with/rate-without) for different setups.

Table D1: Gammas created in thick iron

	Atten. factor	ratio	ratio
7/16" Fe plate	0.5289		
2/16" Pb plate	0.9175		
product of above	0.4852	1.000	
Pb + Fe	0.4787	0.987	1.000
Fe + Pb	0.4577	0.943	0.956

The data show evidence that gammas are created by neutrons interacting with iron, which are (partially) absorbed in the lead. The (absorbed) gamma rate, as detected in the photo tube, is 4-6 % of the "absorbed" neutron rate, which was 47% for the Fe sample used.

Table D2: Gammas created in Boron absorber (Boraflex sheet).

	Atten. factor	ratio	ratio
1/8" Boraflex	0.0262		
1/8" Pb	0.9175		
product of above	0.0240	1.00	
1/8" Pb + 1/8" Boraflex	0.0238	0.99	1.00
1/8" Boraflex + 1/8" Pb	0.0134	0.56	0.56

It is known that each absorbed neutron creates 0.94 gammas of 0.48 MeV. 1/8" of lead absorbs about 50% of such gammas. For neutrons absorbed in the Boraflex instead of the borosilicate window of the tube the signal rate due to gammas is about 2% of the rate created by neutrons in the tube if not absorbed before the tube.